A Consortium for Ocean Circulation and Climate Estimation – JPL

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Grant Numbers: N0001400F0038, N0001401F0378
http://ecco.jpl.nasa.gov/external , http://www.ecco-group.org/

LONG-TERM GOALS

The project's goal is to advance ocean data assimilation into a quasi-operational tool for studying ocean circulation. Observing the complete state of the ocean is difficult owing to its turbulent nature and the sparse and limited measurements. This project will establish a routine description of the global ocean by optimally combining available observations using a general circulation model, to monitor, to assess, and to understand ocean circulation. The effort further aims to demonstrate the practical utility of ocean observing systems by developing applications of such syntheses.

OBJECTIVES

The project's central technical goal is to establish a complete global ocean state estimation over the 16-plus year period from 1985 to present at 1/4º resolution with complete error descriptions, combining all available large-scale data sets with a state-of-the-art general circulation model. Of particular interest is understanding processes underlying the recent 1997-99 El Niño/La Niña event and the possible shift in the Pacific Decadal Oscillation in 1999. Tools necessary for such synthesis will be advanced, including improvements in models and assimilation techniques, with an emphasis on devising practical solutions in marshaling diverse data sets and large numerical models on a routine basis. The effort will exploit existing and ongoing oceanographic experiments (e.g., WOCE) and satellite missions (e.g., TOPEX/POSEIDON) and will support planned experiments including the Climate Variability and Predictability Program (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE).

APPROACH

Advanced data assimilation schemes and state-of-the-art numerical ocean general circulation models are employed to analyze global oceanographic observations. The model is based on a parallel version of the MIT ocean general circulation model (Marshall et al., 1997) that exploits massively parallel supercomputers. The present model extends from 80°S to 80°N with a fairly high resolution (1° by 0.3° within the tropics, with 10m near surface layers) and employs advanced mixing schemes to best simulate diabatic processes. A hierarchical assimilation system is devised for computational efficiency that consists of a Kalman filter and smoother (KFS), the adjoint method, and a Green's function method. The approach is characterized by the physical consistency of its solution's temporal evolution (Figure 1). I.Fukumori, T.Lee, and D.Menemenlis are technical leads in the KFS, adjoint, and Green's function assimilations, respectively. L.Fu is responsible for programmatic oversight, and V.Zlotnicki is investigating high-frequency ocean bottom pressure variations. This project is part of a larger consortium formed under the National Oceanographic Partnership Program (NOPP). The synergistic efforts of the consortium elements are described below ("RELATED PROJECTS.")

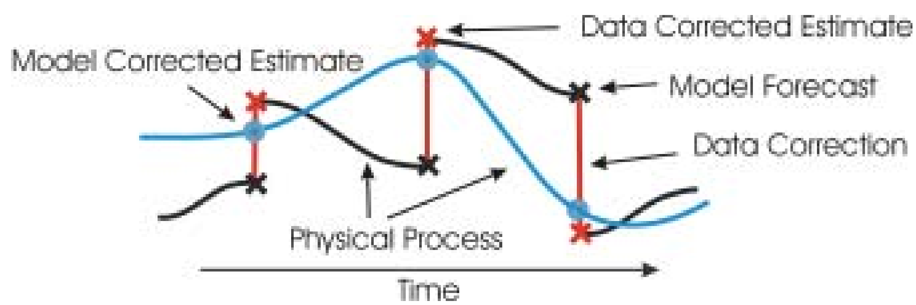

Figure 1: Schematic of data assimilation. [Typical sequential assimilation corrects the model state periodically by observations (from black to red crosses), resulting in changes (red line) that are not accounted for by physical processes (black curve). A physically consistent evolution is achieved by correcting model error sources (blue circle and blue curve).]

WORK COMPLETED

A hierarchical assimilation system has been established for producing routine analysis of ocean circulation. A series of Green's function are computed to correct gross errors in the model's time-mean state; a Kalman filter and smoother (KFS) are employed to produce near real-time, routine analysis of the time-evolving state; the adjoint method is utilized to periodically optimize the state estimates. Satellite and in situ observations are assimilated covering the period from 1993 to present (September 2002) that include sea level (satellite altimetry), temperature and salinity profiles (hydrography), and sea surface winds (satellite scatterometry). These results constitute one of the largest data assimilated model estimates of the ocean to date. A data server has been established (Live Access Server at http://www.ecco-group.org) that makes these results available to the general oceanographic community.   A novel approximation of the KFS has been developed and implemented termed the Partitioned Kalman filter and smoother (Fukumori, 2002) that permits scaling the assimilation system to ultra high-resolution models. Analyses and additional information are provided at the JPL-ECCO server, http://ecco.jpl.nasa.gov/external/.

RESULTS

Data assimilated global ocean circulation estimates are being analyzed to study mechanisms of seasonal-to-interannual changes of the ocean. In particular, water mass exchange between subtropical and tropical regions of the Pacific Ocean has been hypothesized as being part of a mechanism controlling inter-decadal changes in the nature of El Niño (Gu and Philander, 1997). The pathway of this exchange is analyzed based on the model estimates using a simulated passive tracer and its adjoint (Figure 2), the evolution of which describe, respectively, where the tracer-tagged water mass goes to and where it comes from. Over ten years, on average, water mass of the Nino3 region can be traced back (Figure 2a) to eastern subtropical thermocline waters of the northern (27%) and southern hemispheres (39%). The circulation towards the equator occurs along distinct pathways (Figure 2b); along the western boundary (“WB”), interior of the ocean (“Interior”), and along the seaboard of North America (“Coastal”). The Nino3 water subsequently returns to these subtropical latitudes in the upper ocean (Figure 2c). But in contrast to the hypothesized "Subtropical Cell" (STC; McCreary and Lu, 1994), this circulation is an open-circuit with water returning, not to the source region of the exchange, but to the western regions of the two hemispheres (subtropical gyres) and to the Indian Ocean.

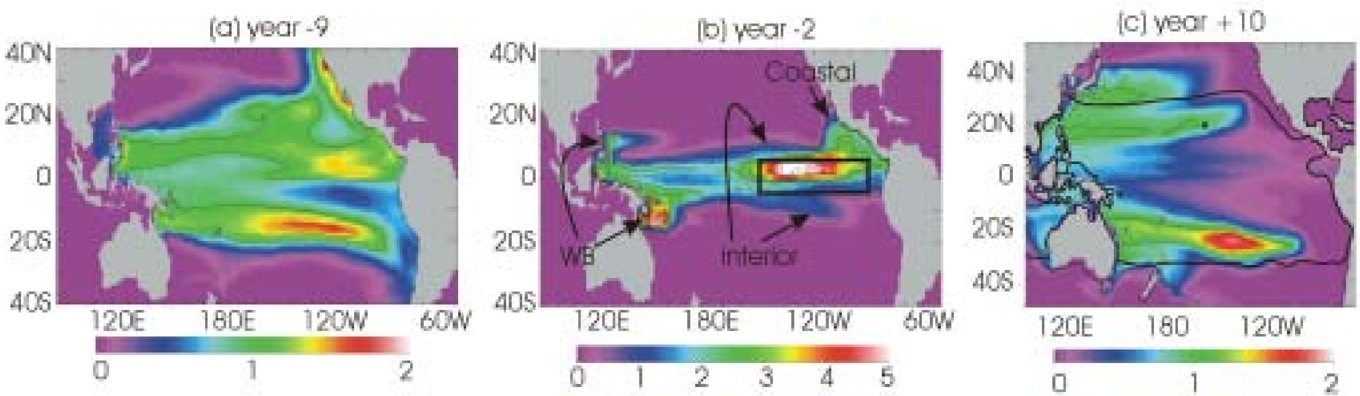

Figure 2: Horizontal distribution of Niño3 water mass at year -9 (a), year -2 (b), and year +10 (c) from reaching the surface of the eastern equatorial Pacific (Niño3 area boxed in (b); 150ºW~80ºW, 5ºS~5ºN). Figure displays integrated content normalized to 10 in Niño3. [The water mass flows equatorwards from the eastern subtropics, and returns poleward to the western subtropics.]

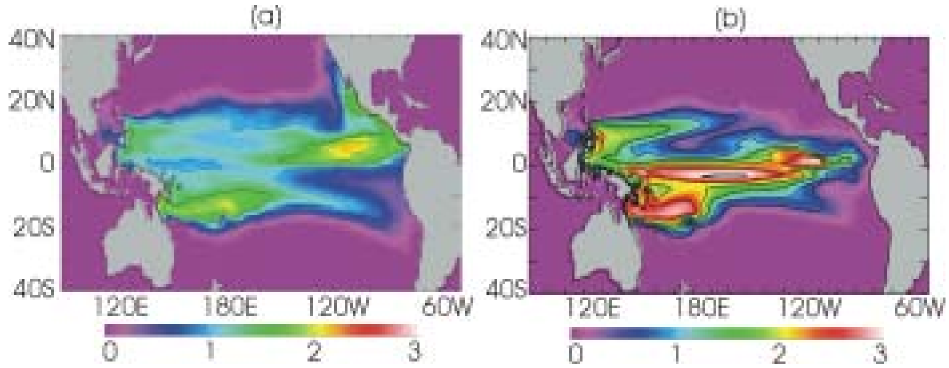

Figure 3: Depth-integrated horizontal distribution of Niño3 water mass at year –5 for different circulation estimates; time-variable circulation (a), time-mean circulation (b). [The interior and North American coastal pathways of subtropical-tropical exchange is much weaker in the absence of intra-annual variability in the circulation.]

Temporal variability causes the tropical circulation inferred from a time-mean state to differ significantly from the average circulation. In particular, non-seasonal, intra-annual variability stirrs the water mass meridionally, significantly enhancing the magnitude of the so-called interior pathway relative to that of the circuitous western boundary pathway (Figure 3). Such short-circuit in the subtropical-tropical exchange can help better explain observed tracer distributions, such as the tritium maximum in the central instead of the western equatorial Pacific (Fine et al., 1981) and the diffusion of observed thermal anomalies as they approach the equator (Deser et al., 1996).

The ocean circulation estimates are also utilized beyond traditional bounds of physical oceanography. For instance, ocean circulation is found to have a major impact on Earth's Polar Motion (Figure 4). Polar motion is the movement of the Earth's rotation axis relative to solid earth (Figure 4a). While angular momentum of the entire Earth system is conserved in the absence of external forcing, relative changes in atmospheric and oceanic circulation can alter the Earth's rotation axis relative to solid earth. Indeed, the combined effects of changes in the atmosphere and ocean is found to explain a larger fraction of observed Polar Motion than that of the atmosphere alone. Moreover, the data assimilated ocean model is found to have higher coherence with observed changes than that without assimilation, demonstrating the fidelity of the ocean data assimilation. The increased accuracy of the ocean estimate allows more accurate assessment of the mechanisms of Polar Motion and other geodetic processes.

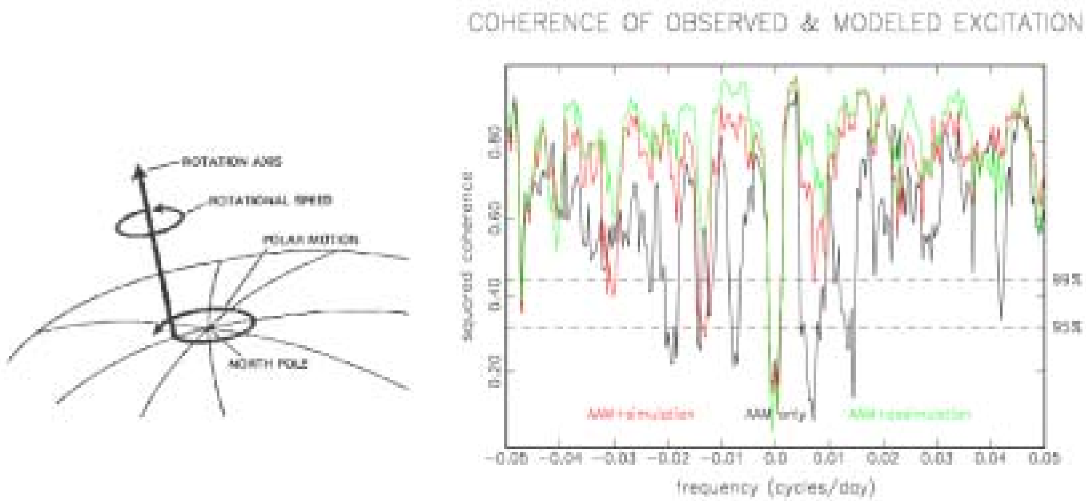

Figure 4: A schematic diagram of Polar Motion (left) and the coherence between observed excitation of Polar Motion and that estimated by models of the atmosphere and ocean (right); atmosphere only (black), atmosphere plus ocean simulation (red), atmosphere plus data assimilated ocean model (green). [The combined atmosphere and data assimilated ocean model has the highest coherence with observed excitation of Polar Motion across practically all analyzed frequencies from –0.05 cycles/day to 0.05 cycles/day.]

IMPACT/APPLICATIONS

Data assimilation's regular and complete description of the ocean facilitates a wide range of studies in ocean circulation and its applications. This is because it is difficult to make inferences about the ocean continuum from individual measurements without knowledge of the surroundings. Processes controlling the state of the ocean and its evolution can be diagnosed and monitored to help detect and anticipate climate variability. Descriptions of ocean circulation also help understand and quantify the carbon cycle and other biogeochemical processes of the ocean that are affected by advection and mixing (see "TRANSITIONS" below.) Data assimilation contributes to practical applications of oceanography that require complete descriptions of the time evolving flow field and thermal structure such as fishing, shipping, search and rescue, industrial and naval operations, and weather forecasting. Model-data syntheses also help identify sources of model inaccuracies, providing an objective basis for ocean model improvement. Additionally, data assimilation helps in the design of optimal observing systems by quantifying impacts of different observing strategies on the accuracy of the syntheses.

Finally, the assimilation system itself (adjoint and PKFS) provides a versatile tool for other applications. The assimilation system can be employed to assimilate other data types and/or applied to other configurations including regional and biogeochemical studies. The MIT general circulation model can also be converted to an atmosphere model, and thus provide a system for atmospheric and/or coupled ocean-atmosphere data assimilations. Application of the model adjoint to sensitivity studies is an emerging area of investigation that provides new insight into the workings of complex systems.

TRANSITIONS

The ocean circulation estimates resulting from this project are being utilized by several external investigators in various applications. These include investigation of the uptake and transport of biogeochemical tracers (carbon, oxygen, nitrogen, and nutrients) (M. Follows, MIT; J. Randerson, Caltech), carbon-cycle modeling (N. Gruber, UCLA; C. LeQuere, MPI, Germany), studies of the effects of ocean circulation on earth rotation (R. Gross, JPL), and changes in Earth's gravity field (J. Dickey, JPL).

Within the ECCO consortium (see "RELATED PROJECTS"), this effort has helped early development of the parallel MIT ocean circulation model and has spearheaded the creation and application of its adjoint. Experience gained from exploring the synergism between the adjoint and KFS approaches will help advance the consortium's complementary investigations.

RELATED PROJECTS

This project is part of a larger consortium formed under the National Oceanographic Partnership Program (NOPP). The consortium, entitled "Estimating the Circulation and Climate of the Ocean" (ECCO; http://www.ecco-group.org/) consists of groups at the Scripps Institution of Oceanography (SIO; D. Stammer, PI), Massachusetts Institute of Technology (MIT; J. Marshall, PI), and the present effort at JPL. The MIT group is the lead in forward model development, while SIO and JPL are leads in data assimilation. Assimilation efforts at SIO and JPL are closely linked and synergistic. The focus of the SIO group is on optimal assimilation utilizing a comprehensive set of observations whereas the JPL group is focusing on high resolution near real-time analyses. The trade-off between optimality and scope is justified given present limitations in computational resources. The two approaches will merge as knowledge and experience is gained by the complementary studies and as additional computational resources become available.

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